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COCKPIT AUTOMATION AND MODE CONFUSION:

THE USE OF AUDITORY INPUTS FOR

ERROR MITIGATION

by

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In Partial Fulfillment of the Graduation Requirements

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14. ABSTRACT

The application of computer technology in modern cockpits has resulted in sophisticated automation that has created situations of mode confusion where the pilot is uncertain about the status or behavior of cockpit automation. Based on current levels of cockpit automation, classifications of mode confusion, and clinical knowledge concerning human cognitive and attentive processes, could an audible attention step help mitigate unrecognized mode error? The Software-Hardware-Environment-Liveware model forms a framework for the analysis of government and academic research concerning pilot automation experiences and use, cognitive models, information and decision processing, and the auditory attention channel. Pilot experiences and several aircraft accidents suggest that mode error is both common and potentially dangerous enough to warrant attempts at mitigation. Studies indicate that the monitoring requirement levied by automation lowers pilot system situational awareness without providing sufficient or proper feedback. Operators can also suffer from cognitive lockup and task channeling, which makes attention diversion difficult. An auditory input might provide an effective attention step if it demands appropriate attention, provides situation reporting, and offers problem guidance. These requirements might be fulfilled if the content is predictive, informational, localized, properly timed, and the theories of effective auditory characteristics proposed by Human Factor?s research are considered.

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Preface

The highly automated flight management systems in today's aircraft cockpit barely resemble the stick and rudder flight controls of yesteryear. Unfortunately, current automation and associated user interfaces are not always intuitive or infallible. Complex cockpits, faster, more capable aircraft, airspace saturation, and increasing air traffic control requirements create the environment and conditions conducive to mode confusion. This problem is both real and personal. With over 20 years in civilian aviation and 5000 hours of worldwide military flying experience ranging from the basic Cessna 150 to the highly automated Boeing 757, I have both witnessed and suffered from this malady. Reducing mode error will require a multifaceted approach involving designers, trainers, and aircrew. My research investigates one possible piece of the total solution by exploring audible attention steps that might quickly and properly identify modal problems to pilots without further burdening their situation awareness with more automated clutter.

The seed for this idea was planted when I was at a commercial air carrier's training center learning how to fly the B-757 for the Air Force. The opportunity for organized research presented itself by way of an Air University Research topic submitted by Air Mobility Command. I owe great appreciation to my Faculty Research Advisor, Lt Col Steve Kimbrell, for his repeated admonitions to keep the research manageable, and for providing the needed focus to sufficiently narrow the scope of my research.

Abstract

The application of computer technology in modern cockpits has resulted in sophisticated automation that has created situations of mode confusion where the pilot is uncertain about the status or behavior of cockpit automation. Based on current levels of cockpit automation, classifications of mode confusion, and clinical knowledge concerning human cognitive and attentive processes, could an audible attention step help mitigate unrecognized mode error? The Software-Hardware-Environment-Liveware model forms a framework for the analysis of government and academic research concerning pilot automation experiences and use, cognitive models, information and decision processing, and the auditory attention channel. Pilot experiences and several aircraft accidents suggest that mode error is both common and potentially dangerous enough to warrant attempts at mitigation. Studies indicate that the monitoring requirement levied by automation lowers pilot system situational awareness without providing sufficient or proper feedback. Operators can also suffer from cognitive lockup and task channeling, which makes attention diversion difficult. An auditory input might provide an effective attention step if it demands appropriate attention, provides situation reporting, and offers problem guidance. These requirements might be fulfilled if the content is predictive, informational, localized, properly timed, and the theories of effective auditory characteristics proposed by Human Factor's research are considered.

Part 1

Introduction

The twentieth century has witnessed the rapid development and marriage of two momentous technologies: the aircraft and the computer.[1] Today, highly automated aircraft make the pilot more of a manager than an active flyer. Ergonomic design has not kept pace, especially in the man-machine interface.[2] This has produced situations of mode confusion where the pilot misunderstands the behavior of cockpit automation. Usually, the result is benign inconvenience, but it has occasionally ended in tragedy.[3]

The Research Question. There are basically two approaches to reducing human error.[4] The first is to determine the underlying reason for the problem and then correct it. For the conditions discussed in this paper, this approach is necessarily equipment specific and therefore might entail a change in design.[5] The second approach is to mitigate the problem by quickly and properly identifying the situation to the pilot for diagnosis and action. This identification step must address the most common mode confusions to be useful, fit within the pilot's cognitive framework to be effective, and demand sufficient attention to be correctly recognized. Traditional cockpit designs use visual and auditory inputs to perform the alert function. Therefore, based on current levels of cockpit automation, classifications of mode confusion, and clinical knowledge concerning human cognitive and attentive processes, could an audible attention step help mitigate unrecognized mode error?

Conceptual Framework. The research question is basically one of ergonomics since this is primarily a man-machine interface issue. The field of Human Factors has developed the Software-Hardware-Environment-Liveware (SHEL) model to conceptualize these types of relationships. To facilitate analysis, this model forms a framework that breaks the situation down into four arms.[6]

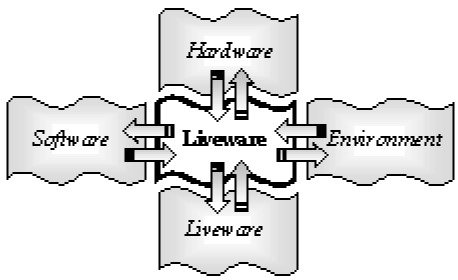

Figure 1. The SHEL Model[7]

The "Liveware" at the center of the cross is the pilot. The other parts of the model constitute the situation that surrounds the Liveware. The pilot interacts with and gets feedback from each of these four parts (represented by arrows going both directions) thus forming four "arms". The Software arm deals with procedures and computer programs. Checklists, Flight Operation Procedures, and Flight Management System (FMS) software logic and internal decision algorithms fall into this category. The Hardware arm covers cockpit layout and controls such as displays and the types and placement of alerts (caution lights, speakers, fire bells). These two arms will be analyzed first by examining pilot's perceptions about cockpit automation, and then investigating the possible consequences of mode confusion in order to determine if they present potentially dangerous enough situations to warrant an attention step.

The next arm, Environment, is concerned with the mental and physical stresses imposed on the Liveware. The mental aspect is addressed with an analysis of the cognitive approaches pilots use to deal with cockpit attention and workload requirements. The physical side is discussed with

Human Factors studies that explore the most effective timing and type of auditory attention steps. Because this is a man-machine interface issue, the Liveware arm is only considered as it relates to workload disturbances. Examples include Air Traffic Control (ATC) communications and interactions with other crewmembers. These not only affect mental performance but also give clues as to the effectiveness of auditory inputs. Finally, each arm of the SHEL model is reassembled to provide specific recommendations on auditory formats that might effectively serve as attention steps for error mitigation.

Research Scope. Efforts at reducing mode confusion are receiving government and academic attention at the international level.[8] This research is but a small part of the larger effort and is limited to exploring auditory inputs for error mitigation. Specific system or cockpit redesign or the use of other sensory channels is not addressed. Similarly, cost factors, specific aircraft implementation feasibility, or design criteria are not included.

Notes

[1] Raja Parasuraman, and Victor Riley, "Humans and Automation: Use, Misuse, Disuse, Abuse," *Human Factors* 39, no. 2 (June 1997): 230.

[2] P. Douglas Arbuckle, et al, "Future Flight Decks," Proceedings of the 21st Congress International Council of the Aeronautical Sciences, Melbourne, Australia, 13 - 17 September 1998, 10.

[3] Asaf Degani, Michael Shafto, and Alex Kirlik, "Modes in Automated Cockpits: Problems, Data Analysis, and a Modeling Framework," Proceedings of 36th Israel Annual Conference on Aerospace Sciences, Haifa, Israel, 1996. n.p.; online, Internet, 4 October 1999, available from http://olias.arc.nasa.gov/publications/degani/modeusage/ modes2.html.

[4] Frank H. Hawkins, *Human Factors in Flight*, ed. Harry W. Orlady, 2nd ed., (Brookfield, Vt.: Ashgate Publishing Co., 1993), 50.

[5] R. Onken, *Functional Development and field test of CASSY - a knowledge-based cockpit assistant system*, AGARD Lecture Series 200: Knowledge-Based Functions in Aerospace Systems, Quebec, Canada: Canada Communication Group, November 1995, 4-3.

[6] Hawkins, 22.

[7] Ibid.

[8] Parasuraman, 250.

Part 2

Background: The Pilot-Cockpit Automation Relationship

Anecdotal evidence suggests that where there is a man-machine interface of any complexity, there is modal confusion.[1] The first question is whether pilot misunderstanding of automation is of a significant enough consequence to warrant efforts at mitigation. If so, then what type of mode confusion either currently is or holds the most potential to be the greatest threat to aviation safety? Due to the serious nature of aircraft safety in terms of lives and financial cost, there has been ongoing research into the actual effects of mode confusion. These studies help define the problem and level of concern by investigating pilot interactions with the Hardware and Software aspects of the SHEL model.

Pilot Perceptions

Addressing the perceptions of pilots that fly automated aircraft forms a starting point for a mode confusion analysis. The Royal Air Force Institute of Aviation Medicine and the University of Illinois/NASA (National Aeronautics and Space Administration) Ames both studied the pilot attitudes of 443 and 168 crewmembers respectively who flew highly automated glass aircraft (A320, B747-400, B757/767).[2] The results were strikingly similar. Both studies found that current automation does not provide sufficient, proper feedback. Audible or visual alerting was also missing, making failures difficult to comprehend and correct. Additionally, increased monitoring requirements lead to complacency and loss of basic scanning flows and flying skills.

Participants also felt that automation actually increases workload during high task phases.[3] This is due to the progressive nature of flying. Pilots do not have the luxury of "pulling over" to the side of the road like in an automobile to figure out a situation. The aircraft continues to move on a three-dimensional path even if the pilot is not aware of the current aircraft configuration or is not prepared for future tasks and situations. The myriad number of situations possible require that an automated system must be capable of complex programming, which in-turn requires time and thought. Thus the actual workload may increase, especially with rapid ATC commands in a congested terminal area. Without audible alerts, the pilot may be unaware of system status.

The second study found that over 80 percent of respondents experienced aviation surprises, of which 39.3 percent of these never discovered why and 42.9 percent had to have it explained.[4] These surprises took two forms; automation failed to take the expected action, or it took an uncommanded unexpected action.[5] Researchers concluded that automation surprises are due to poor mental models, low system observability (no displays or alerts), and a highly dynamic situation where pilots look for commanded actions instead of actual behavior. Recommendations included increasing auditory and visual feedback to promote parallel information processing.[6]

Automation Surprises

As was discussed, current automation has the potential to surprise pilots with its behavior. But just how consequential are these surprises? In 1995 the Federal Aviation Administration Aircraft Certification Directorate commissioned a study on modern glass cockpit automation interfaces in response to several aviation accidents blamed on automation confusion.[7] The global commercial jet airline loss rate has remained constant since 1975, even though the number of departures has almost tripled.[8] From 1987 to 1996, 71.7 percent of the 71 percent of accidents with known causes were blamed on aircrew.[9] The study expressed concern about the level of

pilot understanding, use, and modal awareness of automation, stating that when the pilot is not sufficiently engaged, he enters a "hazardous state" of awareness.[10] They do not feel the problem is procedural since 20 years has not seen a drop in the aircraft loss rate even with airline emphasis on standardization. They recommend task-based displays, real-time system fault management, and higher pilot knowledge levels concerning automation.[11]

An altitude deviation is one common consequence of mode confusion that contains accident potential. NASA Ames researched 500 reports from the Aviation Safety Reporting System (ASRS) and found this to be the most reported problem. In glass cockpits, Air Traffic Control detected half the occurrences, while for flight crews, the altitude alerter only prompted 10 percent of the recoveries. The researchers recommend better and redundant feedback loops for anomaly detection, as well as new system designs.[12]

Modes in Human-Automation Interaction

It has been established that mode confusion occurs and can have significant consequences, but how often are errors committed, and of what type? Between 1997 and 1998 a University of Texas Research Team conducted Line Operations Safety Audits on 184 crews with three airlines. They found that 68 percent of crews committed at least one error, the largest of which (31 percent) was associated with automation. Most were a failure to verify settings (65 percent). Incorrect switch or mode selection constituted 21 percent. Over one-half of errors were not corrected (53 percent), 36 percent were fixed, and 11 percent were mismanaged. A majority of outcomes were inconsequential (85 percent), although 12 percent resulted in an undesired aircraft state with altitude deviations being the most common.[13]

A NASA Ames study conducted on 30 flights aboard B757/767 aircraft helps categorize mode confusion. One of the pilot's functions is to modify and monitor the automation's interface

and control modes. These actions range from manual, to semi-automatic, to fully automatic in nature. Automation behavior is intuitive if it is represented in a display to the crew, or unintuitive if it is based on an unknown internal value or reference.[14] The researchers categorize mode confusion into two areas. The first is misidentification of automation behavior when its actual behavior is different from what was expected. The second is where the pilot acts on the assumption that the machine is in one mode, when it is really in another.[15]

Discussion

Analyses of pilot's perceptions of highly automated cockpits reveal that they feel their job is more systems management than actual hands on flying, which erodes their scanning and basic flying skills. All agree that increased diversified feedback, auditory and visual, is needed to ascertain automation status and behavior. Even though airlines have made concerted procedural standardization efforts, the specter of several recent automation related accidents combined with a fairly constant rate of pilot induced aviation accidents since 1975 infer that procedural change alone has not substantially impacted mode confusion. There is also ample evidence in the NASA ASRS database of mode confusion that contributed to altitude deviations. In addition, studies show that a majority of crews make automation errors on most flights, most of which are not understood or corrected, with 10 percent resulting in an unintended aircraft configuration. Studies of mode usage reveal that confusion falls into basically two camps; misidentification due to expectations, and actions based on incorrect assumptions about the engaged mode.

A Catholic University of America study on how operators use automation provides further support for these observations. They found that designers build the human role around the automation, leaving the operator to manage the resulting system.[16] They assume the user will operate the machine in a certain way, yet have to trust them to use their own judgement in

dealing with diverse situations. Predicting trust and use of automation is very difficult, thereby exacerbating the problem of human-centered design.[17] This has resulted in insufficiently designed displays and feedback mechanisms that actually lower operator mode awareness.[18] The monitoring function removes the operator from the situation. The further removed the pilot, the more the attention step must overcome.[19] Suggested alerts are those that offer prediction, system perception, and sufficient time to respond to high consequence conditions (not just tell of a dangerous situation that already exists).[20]

These discussions have established that mode confusion exists, but do not specify what types of confusions warrant a separate attention step. For this discussion, *mode confusion* will be defined as a human misunderstanding of an automated mode, whether it is an unrecognized fault or an unrecognized behavior. This may be broken down into *designed behavior*, which is either an active behavior (an action, mode switch or capture) or a passive behavior (did not act, switch, or capture), both determined by internally referenced values or states. This type of misunderstanding of this area can be overcome with redesign or operator knowledge, and is not addressed here. The second part is *error*, which is the failure of the automation to behave in the designed active or passive manner (a mode switch or capture, or a specific action) due to a temporary anomaly or internal fault. This failure, such as the conditions leading to an altitude deviation, or a missed localizer (LOC) or glideslope (GS), is the situation that this paper is addressing for an attention step.

It is interesting to note that the above studies mention specific system deficiencies such as insufficient feedback and display of automation faults. They allude to the idea that proper audible alerts might overcome these design shortcomings. The next two sections explore what types of audible alerts might be most effective for mode error.

Notes

[1] Asaf Degani, “On the Types of Modes in Human-machine Interactions,” Proceedings of The Ninth international Symposium on Aviation Psychology, Columbus, Ohio, 28 April - 1 May 1997, n.p.; online, Internet, 4 October 1999, available from http://olias.arc.nasa.gov/publications/ degani/osu97/osu97.html.

[2] Marianne Rudisill, "Line Pilots' Attitiudes about and Experience with Flight Deck Automation: Results of an International Survey and Proposed Guidelines," Proceedings of the Eighth International Symposium on Aviation Psychology, Columbus, Ohio, 1995, 2.

Nadine B. Sarter, and David D. Woods, “Team Play with a Powerful and Independent Agent: Operational Experiences and Automation Surprises on the Airbus A-320,” *Human Factors* 39, no. 4 (December 1997), 558.

[3] Rudisill, 5. Sarter, 562.

[4] Ibid., 558-559.

[5] Ibid., 567.

[6] Ibid., 554-556.

[7] Arbuckle, 13.

[8] Ibid., 2.

[9] Ibid.

[10] Ibid., 5-6, 10.

[11] Ibid., 12.

[12] Asaf Degani, Sheryl L. Chappell, and Michael S. Hayes, "Who or What Saved the Day? A Comparison of Traditional and Glass Cockpits," The Sixth International Symposium on Aviation Psychology, Columbus, Ohio, 29 April - 2 May 1991, online. Internet, 4 October 1999, n.p.; available from http://olias.arc.nasa.gov/personnel/ people/asaf_degani/asaf_publ/osu_alt91.html.

[13] James R. Klinect, John A. Wilhelm, and Robert L. Helmreich, "Threat and Error Management: Data from Line Operations Safety Audits," Proceedings of the 10th International Symposium on Aviation Psychology, Columbus, Ohio, 3 - 6 May 1999, online, Internet, 4 October 1999, n.p.; available from http://psy.utexas.edu/psy/ helmreich/osu99/osu_kinect.pdf.

[14] Asaf Degani, and Alex Kirlik, "Modes in human-Automation Interaction: Initial Observations about a Modeling Approach," Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics Conference, Vancouver, Canada, 1995, online, Internet, 4 October 1999 n.p.; available from http://olias.arc.nasa/gov/publications/degani/modeusage/ modes1.html.

[15] Degani, “Modes in Automated Cockpits,” n.p.

[16] Parasuraman, 232.

[17] Ibid., 238.

[18] Ibid., 232.

[19] Ibid., 248.

[20] Ibid., 243-244, 249.

Part 3

Cognitive Models and The Auditory Channel

The Environment and Liveware arms are addressed by analyzing pilot cognitive processing models to ascertain the best timing for an attention step. In addition, a review of clinical auditory research provides clues to determine what might be the most effective auditory input.

Human Cognitive Information Processing Models

The University of Illinois study cited incorrect mental models as one aspect leading to automation surprises. The cognitive models that pilots employ to process information and prioritize workload provide insight into when an audible attention step might be most effective.

Workload

The Time/Intensity Relationship. As previously discussed, the very nature of flight is dynamic and temporary. Intuitively, it seems that the less time that is available to complete a task, the less likely it is that a correct solution will be achieved. A University of Toronto study investigated the relationship between a time-based factor and an intensity-based factor (information load) to determine a quantitative workload and to test human processing capacity. A simulated ATC environment was used to construct a complex cognitive task.[1] As expected, time pressure is more of factor in determining performance than information load.[2] Therefore, on every flight pilots automatically face a situation where performance is challenged.

Task Complexity, Time, and Monitoring. Previous research suggests that humans do not monitor for failure very efficiently. Additionally, dependence on automation may desensitize pilots to other inputs that do not agree with the automation.[3] Another Catholic University of America study tested subjects in a realistic flight simulation package where they performed single and multiple tasks while monitoring for failures.[4] The researchers found that vigilance decreases with time, and that failures are noticed more often when subjects are manually involved in the task that failed, as opposed to just monitoring automation.[5] However, if manually involved in a task separate from the failed system, monitoring is less efficient.[6] This research highlights monitoring efficiency as a critically important human limitation. This is reflected in the antidotal observation (origin unknown) that flying is basically hours of sheer boredom followed by moments of stark terror. Automation supplies the boredom by imposing a monitoring requirement, then presents terror with an unforeseen situation that resulted from unrecognized mode error due to insufficient alerting.

The Model Degree of Automation for Predicting Mental Loads. Automation does not always reduce workload since the nature of the task and the required monitoring function has to be considered. The Delft University of Technology in the Netherlands worked on formulating a criteria (a Model Degree of Automation) for determining what functions should be automated based upon operator manual task demand (workload), number of automated functions (task criticality) and mental loads (mental calculations).[7] They found that there is a break-even point for automation, where more actually lowers performance. This is due to lower situational awareness if an operator is required to takeover higher level functions, a loss of skill, decreased vigilance with time (lower system awareness), and the idea that the monitoring task itself imposes a mental workload.[8] Additionally, depending upon the nature of the task, mental

workload may not decrease with automation use since the user may make backup mental calculations to reinforce trust in the system.[9] Researchers recommend balancing human involvement (increased situation awareness) with automation efficiency.[10]

Information and Decision Processing

Decision Processing Model. One facet of mental workload is the method of information processing. NASA Ames conducted a series of studies on professional pilots from two major US airlines to determine what influenced their decision making process, and if experience was a factor. They found that pilots' balance perceived risk with time available, only considering multiple options if time allows.[11] The time-limiting nature of flight sometimes requires the pilot to act (or lockup, described below) either impulsively based on a hunch or instinctively based on experience. The military, police, and pilots are just a few occupations that use repetitive training (experience) that is designed to elicit automatic responses when faced with certain situations. Even driving an automobile can require the driver to make split second risk/time decisions, such as swerving or slamming on the brakes to avoid an unexpected obstacle depending upon other threats (oncoming car).

Pilot Information Categorization. In order to take the most appropriate action, decisions require a task prioritization scheme for categorizing information. A NASA Ames study on how pilots categorized information involved 52 pilots from eight different airlines.[12] The researchers found that pilots' rank information as strategic or tactical, and use the source (where it originates from) and destination (where it is displayed), to get clues about content.[13] Generally, information is grouped as aviate, navigate, communicate, or systems administrate, where safety is first, followed by time critical tasks.[14] This decision scheme is central to military flight training, and is stressed for every situation faced. The plane never stops flying and must be controlled (aviate), it

will proceed on a certain path (navigate), others must know of the situation in order to help or get out of the way (communicate), and the aircraft must be managed to rectify or mitigate the problem and configure for landing (system administrate). Only a safety of flight issue should upset this order. A radio call to other aircraft and/or ATC in order to request landing priority or to clear the emergency aircraft's flight path is one such example. Researchers also discovered that information should be presented in multiple channels (auditory and visual), and that scaling (size) and clustering (grouping) help in prioritization.[15] Additionally, automation implicitly adds system knowledge requirements to understand its operation and behavior.[16]

Disturbances and Determinates. For this paper, the Liveware arm relates to human intrusion and disturbance of the cockpit workload. This could be by ATC, another crewmember, or even a passenger. Previous studies suggest that people tend to focus on one problem area to the exclusion of other systems, working sequentially through problems.[17] The TNO Human Factors Research Institute in the Netherlands postulate that operators intervene in automatic functions only to adjust or fix malfunctions, ignoring other systems until the situation becomes too complex to handle (raising the possibility of an accident).[18] Their study had subjects perform a monitoring function that was affected by a number of disturbances that required time limited diagnosis while operating under time constraints.[19] They found that a monitoring activity stops during diagnosis, with resistance to intrusion regardless of other disturbances. Eventually this results in cognitive lockup where monitoring and diagnosis is ineffective.[20] This emphasizes the importance of time, level of monitoring/involvement (situation awareness), and especially proper mental models (decision schemes) to cope with mode errors.

A critical interface that falls under both the Liveware and Environment arms is the relationship between the pilot and ATC. These communications have a direct impact on the

cognitive processes employed in the cockpit. A study conducted by NASA attempts to discern how flight control strategies in complex cockpits is affected by ATC. The criteria are divided into clearance type, predictability, amount of clearances, time constraints, and use of automation. They found that the more intense the environment (larger numbers of commands) and the higher the workload (less time to act), the less automation is used. Initially this seems counterintuitive, although it is hypothesized that manual control allows faster response times and lower mental loads since backup calculations and automation knowledge and monitoring is not required.[21]

The Cockpit as a Distributed Cognitive System. A study by NASA Ames analyzed ten altitude deviation reports in the ASRS by considering the entire system of aircraft, pilots, and controllers as one cognitive structure. This is one example where several agencies are involved in maintaining safety. Errors are considered as either a deviation from expected behavior or expected information. Hypothesizes that for altitude changes there are three cognitive tasks: intention, specification, and execution. Distractions have the greatest impact on execution and cross-checking. The altitude alerting function is not a predictive alert, but is a condition alert, which does not necessarily preempt an altitude bust when the execution and cross-check actions break down. The researchers recommend better cockpit cross-check procedures, and an intelligent audible alert that provides sufficient time for action.[22] The characteristics of this type of alert are discussed below.

The Auditory Attention Channel

In the cockpit environments described, the correct type of audible attention step must be used to maximize the probability that it will demand the proper attention in sufficient time to allow diagnosis and action. Clinical studies on auditory input effectiveness provide possibilities for this attention step.

System Sensitivity versus Dependence of Alarm Monitored Information Sets

Cockpit automation may monitor or control several subsets of systems for the pilot and provide an alert for an anomaly. The question for designers is how to achieve maximum relational efficiency of human and machine monitoring functions. In a University of Dayton study participants performed two tasks concurrently, with one being a signal detection task.[23] The conditions to be monitored were either dependent, partially dependent (overlapping), or independent of automated functions.[24] The most efficient situations are where the man-machine observations are de-correlated, which provides the most information to the operator. The more the monitoring jobs overlap, the less efficient the relationship.[25] They also found that alarms do raise awareness, but they increase the operator workload depending upon how much decoding must be done to achieve proper understanding. Although no specifics were given, they also felt that the alarm effect should be maximized to avoid operator desensitization.[26] This aspect of the alert is explored below. The issue with this study is their definition of efficiency, which was directly related to the amount of information available to the operator. As has been discussed, excessive information may cause cognitive lockup. Additionally, totally de-correlated monitoring tasks place the pilot in the situation of being out of the loop, which lowers situational or system awareness making timely intervention difficult.

Stepping out of pure clinical research into what is occurring in current aircraft design, in 1997 the United States Army Aeromedical Research Laboratory reviewed the current state of aircraft multifunction display and control systems design. Although more concerned with visual displays, they do suggest that auditory warning and advisory systems could take a more complex approach, including providing a more three-dimensional (surround sound) input for threat localization. Messages should be short and to the point, with sufficient time allowed to interpret the auditory input.[27] This idea of sound localization has been researched by the Air Force for use

in helmet mounted displays. The time-for-interpretation idea is discussed in the NASA Ames altitude deviation study and the Catholic University of America research in the form of suggesting predictive warnings instead of real-time situation alerts.

Sound Localization and Content

Sound localization as discussed in the Army paper was researched by the USAF Research Laboratory at Wright Patterson AFB. Localization presents an auditory signal either from or directed to a specific geographic location with the intention of allowing the listener to connect a sound with a point in space. Non-localized signals are for conveying information without drawing or directing attention. For example, for a target directly to the pilot's right, the alert of "target" from an overhead speaker does not provide direction, while the same alert from a speaker at that location or the alert of "target: right" provides direction. Although this work was done to compare localized and non-localized auditory inputs for visual target acquisition and workload in Helmet Mounted Displays, the idea could be extended to other cockpit situations.[28] They found that localized auditory inputs greatly increase target acquisition, reduce head movements, and lower workload. The requirement to monitor objects outside the field of view is also reduced.[29]

A study done by the Massachusetts Institute of Technology reinforces these findings. They researched auditory alarm content and direction for their effectiveness.[30] They found that spatially located sounds and informational content both increase visual target acquisition speed.[31] However, large amounts of information or multiple auditory warnings reduce speed and accuracy.[32] Most people with normal hearing can locate a sound's true location horizontally (on one plane) to 7 degrees plus or minus 3 degrees. The researchers found that six speakers spread evenly (horizontally) is sufficient, with any more being detrimental.[33]

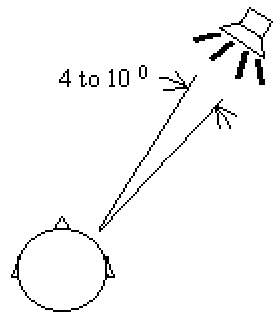

Figure 2. Horizontal (Planal) Geographic Sound Location Ability

Effectiveness of Aural Interruption

Cockpits make extensive use of the visual sense, with auditory inputs used for communication, warnings, cautions, and advisories. If the intent is to provide an attention step, what channel might garner attention more efficiently? The NASA Langley Research Center studied the influence of interruption on the pilot performance of fourteen commercial airline pilots. The original study researched attention steps for datalink communications. Both visual and auditory interruptions were tested.[34] They found that aural interruptions are more effective at gaining attention and response than visual inputs. However, the introduction of another alert in the same channel does not receive the same attention. The reason is one of task focus, with auditory engagement (communications) harder to disrupt once the operator is already engaged in another task.[35] The disturbances study by the TNO Human Factors Research Institute in the Netherlands also supports this finding.

Effective Auditory Inputs

Historical research from the field of Human Factors can provide valuable information on the human auditory sense. Human response to sensory input has been studied for years, with insight on effective auditory input readily available. This research delineates three fundamental principles for the design of auditory alerting signals. It must demand attention, report the nature

of the condition, and provide a guide to the appropriate action. To demand attention, the signal to noise ratio must be such that the input will be intelligible.[36] The alert needs to be reliable, with the correct situational threshold to avoid becoming so commonplace as to be ignored or turned off.[37] To report the condition in an understandable manner, common words and phrases must be used to provide expectancy, and they cannot overlap with other alerts.[38] Designers must remember that humans can absorb large amounts of sensory data, but have small short-term memory capacity, so the messages must be brief.[39] The ideas of localization and content that have already been discussed can help fulfill the guidance principle.

The application of these principles married with the four level safety decision scheme previously discussed has resulted in four categories of alerts. The first level is safety related (impending stall, terrain or traffic warnings), which corresponds to the most important decision aspects of "aviate" or "navigate". The second level concerns aircraft configuration (flaps, gear), which is tied to either "aviate" or "system administrate". The third level relates to system status (fuel, engines), which is "system administrate". The lowest level is communications, such as an intercom "ding" or an ATC datalink light or radio call.[40] Although the last two alerts appear to be out of order with respect to the decision scheme, it must be looked at from both a pilot and a designer perspective. The scheme guides the pilot's actions, so the designer should only include a system alert that identifies an important status or malfunction that either currently is or might deteriorate into a safety of flight issue. The alert's characteristics (fire bell or advisory message) help the pilot rank its importance to the situation. Communication alerts are *prompts* for attention, either from another crewmember or from ATC. If the message is of sufficient importance, the individual will *demand* attention by voice, not by alert. Therefore, the safety reason of the system alert ranks higher than the information reason of the communication alert.

Human Factor's research hypothesizes that there are three functions humans use when receiving auditory inputs. These functions (detection, relative discrimination, and absolute identification) work most efficiently when the input is short, simple, does not have to be remembered for long periods, and relates to an action required immediately.[41] In addition, auditory inputs are more effective when complemented with the visual sense.[42] Thus, the pilot decision scheme, the reason for the alert, and human physiology all should determine the intensity and type of alert. Other factors such as the use of headsets or earplugs should also be considered. Traditionally, alerts range in form from an emergency fire bell and associated warning light to an informational interphone "ding". The dynamic and constantly changing nature of flight coupled with increasing system complexity presents the pilot with ever increasing numbers of alerts. For example, the first intercontinental jet, the B707, had 188 aural alerts. The modern B747 has at least 455.[43]

Discussion

Research indicates that workload and human mental capacity may be a function of intensity, which is information load over time. The higher the load and shorter the time, the less efficient (correct) the performance. In the simplest sense, the basic idea is that automation will lower workload. Why have the pilot manually control the ailerons, rudders, and elevators to stay on course and altitude, turn on and off the fuel pumps, control the engine generator frequencies, constantly adjust the throttles for speed, etc., etc., when automation can just let him watch? This will improve the efficiency of the pilot and allow time for higher level tasks. However, depending upon the nature and criticality of the task and the number of systems automated, workload may not decrease as much as originally thought. This is due to the monitoring task that the automation should receive from the pilot. The very fact that automation exists adds yet

another level of system knowledge that the pilot needs to understand the machine, adding to the task load that monitoring itself imposes. Not only does the pilot have to understand the normal systems (fuel, electrics, hydraulics, engines, flight controls, etc.), but he also has to comprehend the system controlling the systems, determine what it is doing, and program it in short order.

Studies also indicate that humans do not monitor well, with vigilance decreasing over time. Automation and monitoring further remove the pilot from manual tasks, lowering the situational/system awareness as well as reduce flying and scanning proficiency (if there is less hands-on practice). All of these factors combine to raise the pilot’s attention threshold making mode error recognition, diagnosis and intervention more difficult.

According to research, pilots categorize information according to a risk-time model, only considering additional options if time allows. Safety is first, in the general order of aviate, navigate, communicate, or system administrate, with strategic and tactical dimensions. When a disturbance (alert, ATC communication) occurs, people tend to focus on that issue to the exclusion of other duties (to the point of resistance), including monitoring, cross-checking, and task executions. Even additional disturbances may not receive the same level of attention until the original issue is resolved, possibly ending in cognitive lockup. Interestingly, as workload intensity increases, pilots tend to use less automation, preferring to accomplish tasks manually. This is possibly for quicker response, lower mental loads, or higher focus for better performance.

The situation for the pilot as described in the paragraphs above probably oscillates between the extremes of total disengaged boredom to a highly focused concentration on one task to the exclusion of all others. The entire situational spectrum requires a specifically designed attention alert. Research indicates that audible alerts make effective attention steps, especially when used in concert with or in support of visual displays. With this in mind, what audible alert would be

the most effective? A method to approach this question lies in the three principles for alert design. The first guideline is that it must demand attention. Human Factor's research suggests that it must rise above the noise to be intelligible and must be differentiated from the myriad of other audible alerts that are used on modern aircraft to be recognized. It should not be duplicative of normal pilot tasks to the point of becoming a confirmation alert, and be reliable enough so as not to become a nuisance to be ignored during high workloads or times of focus on the diagnosis of other system malfunctions.

The second principle concerns situation reporting. Research suggests that it should contain common language in short message format since short-term memory is limited. Alerts traditionally fall into four categories that range from safety to communications. This should determine the loudness and type (bell, voice, muted tone) of auditory input. Studies repeatedly stress that the informational content should be predictive if possible, allowing enough time for diagnosis and action. This is as important for the disengaged pilot with low situational awareness as it is for the overworked pilot focused on one task.

The third principle, guidance, might be addressed by using localization. This method reduces reaction and acquisition time. Only small numbers of speakers need to be used for general direction or three-dimensional effects. Directing the pilot's attention to an area of the cockpit where the mode error is or has occurred (the switch or display location) could increase reaction time and improve the informational content.

Notes

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[5] Ibid., 318.
[6] Ibid., 319.
[7] Zhi-Gang Wei, Anil P. Macwan, and Peter A. Wieringa, “A Quantitative Measure for Degree of Automation and Its Relation to System Performance and Mental Load,” *Human Factors* 40, no. 2 (June 1998), 278-280.
[8] Ibid., 278, 289.
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[11] Ute Fischer, Judith Orasanu, and Mike Wich, "Expert Pilots' Perceptions of Problem Situations," Proceedings of the Eighth International Symposium on Aviation Psychology, Columbus, Ohio, 1995, online, Internet, 4 October 1999, n.p.; available from http://olias.arc.nasa.gov/publications/fischer/osu/OSU_Ute_.html.
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[13] Ibid., 4.
[14] Ibid., 5.
[15] Ibid., 6.
[16] Ibid., 2.
[17] Jose H. Kerstholt, et al, “The Effect of a Priori Probability and Complexity on Decision making in a Supervisory Control Task,” *Human Factors* 38, no. 1 (March 1996), 67.
[18] Ibid., 66.
[19] Ibid., 65.
[20] Ibid., 78.
[21] Stephen M. Casner, "Understanding the Determinants of Problem-Solving Behavior in a Complex Environment," *Human Factors* 36, no. 4 (1994), 580-596, online, Internet, 4 October 1999, n.p.; available from http://human-factors.arc.nasa.gov/IHI/papers/publications/casner/hf94/hf94.html.
[22] Everett Palmer, et al, NASA Technical Memorandum 108788, Subject: Altitude Deviations: Breakdowns of an Error Tolerant System, July 1993, n.p.
[23] Greg C. Elvers, and Paul Elrif, “The Effects of Correlation and Response Bias in Alerted Monitor Displays,” *Human Factors* 39, no. 4 (December 1997), 573.
[24] Ibid., 570.
[25] Ibid., 573.
[26] Ibid., 572.
[27] Gregory Francis, and Matthew J. Reardon, Aircraft Multifunction Display and Control Systems: A New Quantitative Human Factors Design Method for Organizing Functions and Display Contents, USAARL Report No. 97-18, Fort Rucker, Ala.: U.S. Army Aeromedical Research Laboratory, April 1997, 9.
[28] Todd W. Nelson, et al. “Effects of Localized Auditory Information on Visual Target Detection Performance Using a Helmet-Mounted Display,” *Human Factors* 40, no. 3 (September 1998), 452.
[29] Ibid., 458.

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[30] John S. Wallace, and Donald L. Fisher, “Sound Localization: Information Theory Analysis,” *Human Factors* 40, no. 1 (March 1998), 50.

[31] Ibid., 58.

[32] Ibid., 59, 65-66.

[33] Ibid., 52.

[34] Kara A. Latorella, "Effects of Modality on Interrupted Flight Deck Performance: Implications for Data Link," Hampton, Va.: National Aeronautics and Space Administration, Langley Research Center, 1998, 2.

[35] Ibid., 4.

[36] Hawkins, 262-264.

[37] Ibid., 256.

[38] Ibid., 163, 168.

[39] Ibid., 243.

[40] Ibid., 257.

[41] Ernest J. McCormick, *Human Factors in Engineering and Design*, 4th ed. (New York: McGraw-Hill Book Co., 1976), 123-124.

[42] Ibid., 53.

[43] Ibid., 255.

Part 4

Recommendations and Conclusion

The information presented in the Background, Cognitive Models, and Auditory Channel sections is theoretical in scope. This part narrows and synthesizes these ideas by providing examples of possible real world applications and areas for future consideration.

Recommendations. Table 1 presents several notional scenarios based on the C-32A (B757-200ER) where effective auditory alert principles are applied. These errors were chosen for their possible deadly midair or ground collision potential. Additionally, the autothrottle (A/T) failure example could result in aircraft damage by exceeding the normal operational limits (if at a high thrust setting), or end in a dangerous stall (if at a low thrust setting). Although each aircraft type presents its own possible scenarios of mode error, the examples provided demonstrate how it might be possible to bridge the gap between theory and practice.

The terminology in Table 1 concerns primarily three areas of the cockpit and is generally C-32A specific. For discussion purposes a graphic representation of the forward cockpit is represented in Figure 3. The first area is the Mode Control Panel (MCP) located in the center of the cockpit dashboard. It is where the pilot sets the altitude, aircraft speed, and autopilot mode functions. Selections on this panel include Altitude (Alt) Hold which tells the autopilot to maintain the altitude selected on the MCP.[1] Vertical Navigation (VNAV) selects a vertical profile calculated by the Flight Management System from keypad entries.[2] Flight level change

(FLCH) uses logic based on aircraft performance to change current altitude to that selected on the MCP.[3] Vertical Speed (VSPD) is a dial-in function that sets aircraft climb or descent to a specific foot-per-minute rate.[4] Lateral Navigation (LNAV) performs the same function as VNAV only in the horizontal plane.[5] Approach (APP) mode prepares the autopilot to intercept a Glideslope and/or Localizer on an approach to landing.[6] The GS is a precision beam sent by a ground station that vertically guides the aircraft down to landing. The LOC is a beam that horizontally guides an aircraft to the runway. Together, these form a Precision approach that is used in weather so poor that the pilot may not see the runway until only seconds from landing. All of these modes engage the autothrottles which maintain aircraft speed to that selected on the MCP. Additionally, the MCP has an Exhaust Pressure Ratio (EPR) mode that keeps the A/Ts at a particular dial-in thrust setting.[7]

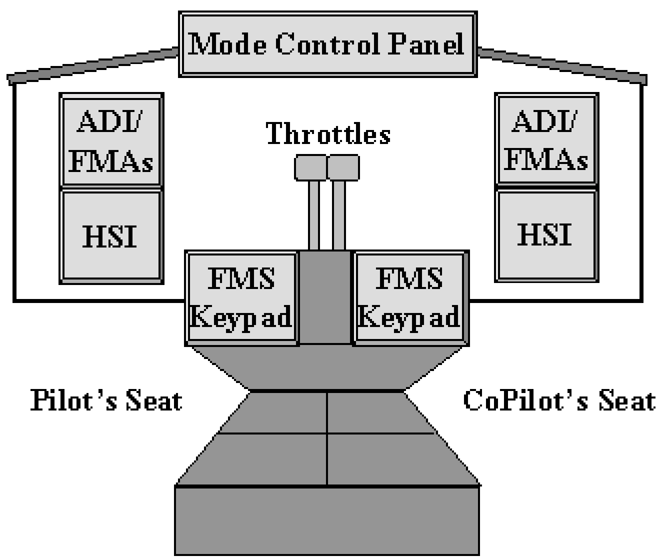

Figure 3. C-32A Forward Cockpit[8]

The second area of the cockpit is the FMS which has entry keypads located on both sides of the center control stand. It is a complex computerized system that integrates pilot entered course and vertical profile information (via keypad), MCP inputs, navigation system guidance, and stored database values to control the autopilot.[9] The third area concerns the relative position

displays located directly in front of both pilots. The Attitude Display Indicator (ADI) presents aircraft pitch and roll relative to the horizon. Also on the ADI are Flight Management Annunciators (FMA) which confirm the status (armed, engaged, captured) of the A/T, autopilot, and any selected modes.[10] The Horizontal Display Indicator (HSI) presents horizontal position relative to the selected FMS course or ground signal (LOC).[11]

The scenarios in Table 1 are presented in terms of the automation mode selected, a possible corresponding mode error, and the mitigating audible alert. Appropriate columns describe how an alert fulfills the three principles suggested by Human Factors studies and the predictive step suggested by other research. Techniques that might intrude into the pilot's cognitive framework are covered under the "Attention" column by volume, sound level, and number of repetitions. The intensity is relative to existing alerts, with "Loud" representing the maximum volume traditionally used. The time (seconds) between alerts and number of repetitions was strictly arbitrary based on criticality of the failure. These callouts provide situational reporting that must be different from any other alerts, such as the "glideslope" warnings provided by the Ground Proximity Warning System (which warns of excessive deviation from the GS ground signal).[12] As illustrated in the third and fifth examples, adding a word is one differentiation method. These callouts are easily modified since software controls the verbiage and intensity of voice alerts in most modern aircraft.

Either localizing or projecting the sound with a small number of well-placed speakers (studies suggest six or less) can enhance both the "Situation" and "Guidance" principles. Speaker location is fixed since the pilot's seats are always in the same place and thus will have the same relative effect for each pilot. The predictive function could be tied to the existing computer logic

used by the FMS to calculate course and altitude intercepts and capture zones. These improvements would be relatively easy to implement and could yield tremendous results.

Table 1. Notional Examples of Mode Error Auditory Alerts

Automation Status		Alert Principles			
Mode	**Error**	**Attention**	**Situation**	**Guidance**	**Predictive**
Alt Hold	Disengages without pilot action	Loud, repeat every five seconds for five times	Callout "Check Altitude"	Callout localized to altimeter, MCP, or FMA	Immediate
Alt in MCP; + VNAV, FLCH, or VSPD	Failure to switch to Alt capture mode within preset logic	Same as above	Callout "Altitude Capture"	Same as above	Callout when alt hits normal capture zone based on preset logic
APP mode engaged	Fails to switch to GS capture mode	Same as above	Callout "Glideslope Mode"	Callout localized to ADI/FMAs	Callout when in normal capture zone based on good GS signal and preset logic
APP or (LOC) mode engaged	Fails to switch to LOC capture mode	Loud, repeat every three seconds for five times	Callout "Localizer"	Callout localized to ADI/HSI and FMAs	Same as above except for LOC
APP, with GS captured	GS disengaged without pilot or GS signal fails	Same as above	Callout "Glideslope Fail"	Same as above	Position exceeds preset tolerance from GS beam
APP or LOC, LOC captured	LOC disengaged without pilot or signal fails	Same as above	Callout "Localizer Fail"	Same as above	Position exceeds preset tolerance from LOC beam
EPR, VNAV, FLCH	A/T disengaged without pilot	Medium, repeat every five seconds for five times	Callout "Autothrottle off"	Same as above	Immediate
LNAV	Fails to switch to FMS course capture mode	Same as above	Callout "Course"	Same as above	Same as above

The ideas presented and synthesized here are only a small part of a greater effort working to understand the man-automation interface issue. Although much emphasis has been placed on multi-seat commercial-type aircraft, the characteristics of mode error make this research even more applicable to complex single-seat aircraft where there is no human backup. The pilot-automation interface, types and consequences of mode confusion, cognitive and information modeling, and Human Factors sensory studies all should continue as each plays a role in the final answer. In the larger sphere, improving human-centered design, using other alerting methods and channels (visual, tactile?), and increasing pilot awareness all deserve attention. These efforts could possibly discover an as yet unknown approach to reducing mode error or its consequences.

Conclusion. The increasing complexity of cockpit automation sometimes results in mode confusion that might be mitigated by an audible alert. The SHEL model provides a basic framework to research this problem. An analysis of the SHEL Hardware and Software arms shows why audible alerts are needed. Studies reveal that a great majority of pilots experience automation surprises whose origins were not immediately understood, if comprehended at all. The mode confusion that occurs falls into two general areas: misunderstanding of designed active or passive behavior; and misunderstanding of mode error (system failure). Increasing pilot system knowledge might reduce the former, while the latter might be mitigated with an appropriate audible alert. Unfortunately, current systems do not provide the type of feedback needed to make these failures understandable. Pilots in advanced cockpits make automation related errors on almost every flight. These errors hold the potential for tragic consequences. Accident rates have remained almost constant even with airline procedural standardization.

One method of mitigating mode error is by introducing an audible attention step. An analysis of the Environment and Liveware arms clarifies what types of audible alerts would be

most effective. Human workload and processing capacity are partially dependent on the amount of information and time available, constituting an inversely proportional relationship with performance. Automation itself does not lower this workload absolutely. The number and type of systems automated as well as the extra knowledge needed to operate and monitor the automation (backup mental calculations and vigilance) determine the true workload level. Humans also do not perform monitoring well especially over time. The less involved the operator, the lower the system situational awareness, and the harder the reorientation in case of malfunction.

In the decision-making process pilots' balance risk with time. Information is prioritized as aviate, navigate, communicate, or system administrate. If already involved in one task, it is difficult to divert their attention, even with additional alerting. Pilots also tend to use automation less with increasing workload, which further channels their attention. This situational spectrum ranges from disengaged boredom to cognitive lockup. Therefore, a predictive, informational system alert that demands attention and intrudes upon the pilot's cognitive state is needed.

The predictive function should address the workload issue and provide the extra time needed for a situationally aware diagnosis. The informational function can reduce this time by focusing the pilot on the correct problem. The attention aspect is addressed in the three principles for effective auditory alerts suggested by Human Factors studies. First, it must demand attention in order to cut through cognitive lockup or task focus. It should be reliable, recognizable above environmental noise, distinguishable from other alerts, and not be duplicative of normal pilot tasks. Second, it should provide situation reporting with short understandable messages commensurate with the degree of urgency. Lastly, it should guide the pilot to the problem mentally and/or literally. A predictive, informational alert that gets a distracted pilot's attention can effectively reduce the recognition and reaction time for mode error.

Notes

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[2] Ibid., 11.31.16.

[3] Ibid., 11.31.2.

[4] Ibid.

[5] Ibid., 11.31.9.

[6] Ibid., 4.20.11.

[7] Ibid.

[8] Ibid., NP.10.4.

[9] Ibid., 11.31.1.

[10] Ibid., 4.10.3.

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